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AIR FORCE FLIGHT DYNAMICS LABORATORY
DIRECTOR OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT PATTERSON AIR FORCE BASE OHIO

THE EFFECT OF SPECTRUM VARIATIONS ON THE FATIGUE BEHAVIOR OF NOTCHED STRUCTURES REPRESENTING F-4E/S WING STATIONS

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FOREWORD

At the request of Messrs. W. J. Crichlow and C. F. Tiffany of ASD/ENF, an experimental and analytical program was performed to evaluate spectrum effects in flight-by-flight loading. This program utilized the basic spectrum being applied to the F-4E Slatted Wing fatigue test article being tested at McDonnell-Douglas Corporation, St. Louis, Missouri and variations of that spectrum. Mr. J. M. Potter performed the analytical fatigue crack initiation studies presented herein. Dr. J. P. Gallagher coordinated the experimental program and performed the crack propagation studies. Mr. H. D. Stalnaker was responsible for the experimental results. This report covers work accomplished from 1 May 1973 to 1 November 1973. The work was done under Project 5068, "F-4E Leading Edge Slat/ASIP".

In a program of this scope, many people from several organizations on Wright-Patterson Air Force Base contributed their special skills to assure the success of the program. Mr. L. E. Zaytoun of the ASD Hybrid Computer Facility, arranged for the load spectra to be translated from the contractor supplied magnetic tape to card format. Mr. R. High and Mr. J. M. Ferguson of the AFAPL developed a set of cards from that deck that were used to program the load spectra applied to the coupons. Mr. N. K. Mondol and Mr. J. G. Anderson of the AFFDL Structures Test Facility, combined the load spectra decks with a mini computer and analog tape unit to produce an analog replica of the load spectra necessary to operate the electro-hydraulic test equipment. Lastly, Messrs. O. B. Jarrels, W. K. Soward, E. C. Murphy

and R. A. Farmer were responsible for operating the test loading equipment, for assuring that the load levels were accurate, and for making the crack length measurements.

This manuscript was released by the authors in January 1974.

This memorandum has been reviewed and is approved.

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Chief, Solid Mechanics Branch
Structures Division

ABSTRACT

This report presents the preliminary results of an experimental and analytical study of the fatigue behavior of structures subjected to flight-by-flight spectrum loading. The spectrum investigated was based on that applied to the lower wing skin of the F-4E Slatted Wing fatigue test article. Spectrum variations without changing spectrum content included peak load rank ordering, order reversal, peak load truncation and low load truncation. Spectrum variations including changing the spectrum content by changing the mission mix were also studied.

The analytical prediction of low load truncation correlated well with the experimental results indicating that the contractor's truncation model adequately modelled the longer spectrum. The analytical predictions for the other basic variations without changing the spectrum content indicated that only a minor variation in fatigue behavior would be expected from spectrum reordering. Changes in the mission mix provided the most significant effect in fatigue behavior.

INTRODUCTION

Predicting the fatigue behavior of structural components subjected to flight-by-flight spectrum loading has always been difficult. As test equipment became more sophisticated and test spectra more complicated, engineers have noted the considerable influence of the spectrum order and content on the fatigue behavior of structures. (1-5)*

At the later stages of the Aircraft Structural Integrity Program (ASIP) related fatigue test program of the F-4E Slatted Wing aircraft, an experimental and analytical investigation was initiated to ascertain the extent of fatigue life variations possible from simple changes in the applied load spectra. With the results of this investigation, it is possible to anticipate fatigue life variations that could result from fleet usage changes by comparison to the single full-scale test point determined in the ASIP.

This paper describes the experimental results and analytical predictions derived from a basic load spectrum and its truncated mate applied to simple notched coupons. Also presented are life predictions made with the Sequence Accountable Fatigue Analysis for basic variations on the applied load spectrum.

* See List of References

Load Spectra

The spectrum applied to the F-4E Slatted Wing fatigue test aircraft contained 320 air-to-ground, 230 air-to-air, and 180 nontactical flights per 1000 flight hours. These were arranged in 100-hour subgroups and were applied in the following order: air-to-air, air-to-ground, and nontactical. The highest loads in the spectrum were randomly scattered throughout the 1000-hour spectrum. The 1000 hour segment was equivalent to 250 hours of air-to-air, 450 hours of air-to-ground, and 300 hours of nontactical flying conditions.

The specific spectrum used in this investigation was developed from the bending moment spectrum to be applied at Load Reference Station (LRS) 140 of the test aircraft. This spectrum, containing both positive and negative load excursions, was truncated at a 2.0 g minimum excursion. The so-called full spectrum was developed by adding the cycles associated with a truncation level of 1.4 g minimum excursion. The full spectrum contained 9135 levels of load for a total of 54,765 cycles per 1000 hours. The truncated spectrum contained 6216 load levels for a total of 19,080 cycles per 1000 hours. The derivation of the spectra is described in Reference 6.

The spectra were obtained from McDonnell-Douglas in digital magnetic tape form. The mag tapes were translated into punched card form. These punched cards were first used to generate the analog magnetic tape to control the electro-hydraulic test equipment. Then the same punched cards were input to the computer with the cumulative damage analysis used to make the predictions published herein.

Test Specimens

Two types of specimens, representing different geometrical severities, were utilized in the experimental phase of this investigation. Specimens were made from 7075-T6511 Aluminum Alloy material. The specimens shown in Figures 1 and 2 contain an elastic stress concentration factor of 3.2 (7) and 6.0 (8) respectively, based on gross stress.

Several specimens of the type shown in Figure 1 were prepared with an 0.125 inch diameter hole which was notched on one side to start a corner crack. The corner crack was initiated from the notch by low level bending stresses. Following this precracking operation, an 0.250 inch hole was drilled in each precracked specimen leaving a small corner crack which extended no more than 0.015 inch from the perimeter of any hole. These specimens were then tested to obtain the propagation behavior of corner cracks growing out of holes which is a typical problem in aircraft structures.

The remainder of the specimens were tested to failure without being precracked. When cracks appeared, they were noted and surface measurements taken at short spectrum intervals until the specimen separated.

Test Procedure

The fatigue tests were conducted using an electro-hydraulic closed loop test system with a maximum capacity of 100 kips force. The axially loaded specimens were held in place with hydraulic locking grips.

The fatigue load spectra were furnished by the contractor on digital mag tape in the form of a list of sequential maximum and minimum loads with the associated number of cycles. A mini-computer equipped with a D-A peripheral converted this list into a continuous analog signal with the consecutive peak loads connected with haversines. The analog signal was then recorded on FM magnetic tape for use as the reference input signal to the closed loop load control system. The peak load spectrum produced in this manner is estimated to be within one percent of the desired spectrum.

The applied test loads were monitored through an independent data system. The output of the data bridge of the load cell was fed, upon signal, through a multiplexer to a mini-computer which sampled the load trace and stored the maximum and minimum load values for 20 cycles. This information is then displayed on a TV screen next to the control equipment. The peak load information is used to decide if the correct loads are being applied. The applied loads were maintained to within three percent of the programmed values.

Fatigue crack initiation and crack growth of the test coupons were visually monitored using binocular zoom microscopes with a maximum magnification of 40X. Mylar scales containing 0.005 inch divisions were attached to the test specimens to obtain surface crack length measurements. The crack lengths were estimated to the nearest 0.001 inch and the accuracy of the crack length readings were estimated to be well within ± 0.002 inch.

Analytical Predictions

All fatigue life predictions presented herein were made using the Sequence Accountable Fatigue Analysis computer program (9). This computer program was developed in-house at the Air Force Flight Dynamics Laboratory to analyze the fatigue behavior of uncracked structures with any general applied load spectrum. The program develops a prediction of damage accumulation by calculating the local stress and strain history at a notch in structural members. The effect of changing the overall sequence of loading is accounted for through the ability of the analysis to calculate residual stresses. The fatigue life effects from spectrum variations such as reordering of loads or low load truncation are accounted for through the cyclic relaxation of the residual stresses. In the general case then, any spectrum variation can be evaluated using the fatigue life predictions developed with this analysis.

The Sequence Accountable Fatigue Analysis calculates the local plastic strain excursions associated with the creation of residual stresses and the resulting elastic local stress cycles during the spectrum. Damage calculations are made and accumulated for both the elastic local stress and plastic local strain cycles. The local elastic stress spectrum is range-pair counted prior to damage accumulation. The residual stress relaxation analysis of Potter (5) is included in the program. The primary effect of the residual stress relaxation is to change the damage accumulation rate of the cycles following the peak loads but it also affects the plastic strain experienced during the peak loads.

The value of the residual stress relaxation constant used in this analysis was that which was determined to give best fit in a similar flight-by-flight spectrum truncation study (8). The resulting residual stress relaxation constant of 2.5×10^6 ksi^2 cycles was used throughout the study.

The fatigue behavior at Butt Line 100 at the edge of the landing gear cutout was of primary interest in this study. Analysis of the results of strain gages placed along LRS 140 during a loads survey indicated that $K_t S_{max}$ = 97.0 ksi properly characterized the stress field around fastener holes at the edge of the cutout. This stress level was analytically investigated for four levels of higher stress as well as four lower levels to cover related components. The analytical results obtained can probably adequately describe the fatigue behavior for the ASIP aircraft at many locations on the lower surface of the wing.

RESULTS AND DISCUSSION

Low Load Truncation

Table 1 contains a listing of all tests conducted in conjunction with this program and the number of flight hours from the start of the test to final fracture. The tests had basic variations in the maximum spectrum stress level, specimen geometry and spectrum type. Figure 3 compares the crack initiation results with predictions presented in Table II made using the Sequence Accountable Fatigue Analysis. The test results basically follow the trend of the predictions. The predictions indicate only a minor decrease in fatigue life

with the full spectrum compared to the truncated spectrum. The number of test results with the full spectrum is too limited to conclusively determine the effect of spectrum truncation. Apparently, there is no significant difference in life due to the truncated cycles because one of the full spectrum results has longer life than, and the other has a shorter life than the truncated spectrum. Furthermore, all results fall within the band of normal scatter about the mean of the predicted life values.

Figures 4 and 5 show the crack length measurements made at the end of each 100-hour block for the truncated and full spectrum tests respectively. To isolate the influence of the truncation of lower level cycles on the crack propagation behavior associated with this spectrum, the results of Figures 4 and 5 were replotted in Figure 6 using a normalized initial crack length of 0.025 inch. Figure 6 demonstrates that there is no observable difference in crack propagation behavior that can be attributed to truncation effects at either of the stress levels.

Table III lists the average growth rates as a function of crack length for both load spectra. Table III shows that the 20% higher stress condition induces growth rates that are a factor of 1.5 faster than the base stress level rates.

Primarily because of the extremely good correlation in crack growth rates for the truncated and full spectrum tests, this office concludes that the contractor's original truncation analysis provided a good model of the full spectrum. The crack propagation behavior

is a good indicator of relative effects because of its greater sensitivity to spectrum effects. The stress state in the localized region around the crack tip more acutely senses remote stresses than that at the root of a notch, and thus, the locally induced stress changes for a given spectrum will be more acute at the crack tip than at the notch root. Therefore, it is reasonable to suggest that spectrum changes that do not induce changes in crack propagation behavior will not result in changes in notch crack initiation behavior.

Spectrum Order and Peak Load Truncation

There are several sets of data where spectrum order changes without spectrum content changes appear to have a significant effect on the fatigue life of structures. In the tests where large differences in life are apparent, the number of cycles between high loads is large. For instance, Nauman, et. al (1) reports on results with block length of between 10,200 and 500,000 cycles while Schijve and Jacobs (2) results have a block length of 81,500 cycles. In a more recent publication, Schijve (3) compares the effect of spectrum order in crack propagation behavior with spectra blocked in 40 cycles versus 40,000 cycles per block. The crack propagation life with the 40,000 cycles per block show significant differences in life when ordered hi-lo, lo-hi-lo and lo-hi while the 40 cycles per block data indicate almost no differences in behavior.

Due to the above potential differences in spectrum order effects, this office analytically investigated two variations on the basic spectrum order. The first variation involved simply reversing the order of the applied load history. The analytical predictions are shown in Table IV. These results indicate that there should be no

difference in fatigue life induced by reversing the order of loading of the 1000-hour block. This behavior occurs because the spectrum was developed with the maximum loads randomly scattered throughout the 730 flights making up the basic block. Since the occurrence of the maximum loads is random, one should intuitively expect no significant differences in their position in the spectrum whether or not it was reversed.

The second variation involved rank ordering all loads above a threshold in a hi-lo and lo-hi manner throughout the 1000-block. Two threshold values were chosen: 85.7% and 78.5% of the highest load in the spectrum. Everytime a load level exceeded the threshold, it was replaced by a value that varied from that threshold value to the maximum depending linearly upon its position in the 1000 hours. The analytical predictions for this case are presented in Table V. The predictions indicate that a life decrease of approximately 20 - 30 percent results from rank ordering whether lo-hi or hi-lo ordering is used. This occurs because the rank ordering has the tendency of clustering the highest (most beneficial) loads together toward one end or the other of the 1000-hour block. This decreases the overall relative frequency of occurrence of these high loads. When the peak loads are clustered, the beneficial residual stresses do not occur uniformly throughout the spectrum and shorter life results.

A detailed observation of the analysis indicates that, at the K_tS_{max} = 97.0 ksi level for instance, only 20 flights are required to make the beneficial residual stress relax completely following the highest load in the 1000-hour block. The effect of the clustering of

the peak loads at the beginning or end of the block is to leave most of the remaining flights with no beneficial residual stresses.

Some early tests by Heywood (4) indicate that peak load truncation can have a significant effect on fatigue life. This occurs primarily because the level of the maximum load determines the level of the residual stress created by that load. For this study of peak load truncation, two levels of threshold were chosen, 85.7% and 92.8% of the maximum load in the 1000-hour block. In the analysis, any load that would exceed the threshold was truncated to that level. The analytical predictions for this case are presented in Table VI and Figure 7. These predictions indicate that little change in fatigue life would be expected. Residual stresses are produced when the maximum stress ($K_T S_{max}$) is above the 72-76 ksi yield stress of the 7075-T6 material used. When peak-load-induced residual stresses are involved, truncation of the maximum stresses can result in decreased life.

The above analysis indicates that spectrum order changes and peak load truncation do not have a significant effect on this particular spectrum provided that the spectrum remains a flight-by-flight configuration without other changes in mission content.

Mission Mix

A detailed examination of the damage causing elements of the full and low load truncated spectra indicated that an inordinate amount of damage resulted from the air-to-air flights. Two spectra were prepared from the low load truncated spectrum in order to specifically investigate the effect of mission mix on the fatigue behavior. The low load

truncated spectrum was split into two: one contained only the air-to-air flights and the other contained the remainder. The low load truncated spectrum was used for the fatigue life analysis because, in going from mag-tape-to-card, this spectrum retained the flight type identifier, whereas the full spectrum did not.

Table VII and Figure 8 present the results of the mission mix study. The analysis indicates that the air-to-air flight spectrum contributes far more damage than the combined air-to-ground and non-tactical flight spectrum on a flight hours to failure basis. The effect of mission mix is shown in Figure 9 by presenting the data of Table VII on an interaction curve basis with life for the air-to-ground and nontactical spectrum on the horizontal axis. The information presented in Figure 9 indicates a straight line functional relation for maximum applied stress (K_tS_{max}) below 140 ksi. Thus it is evident that the damage from the air-to-air flights can be decoupled from the remaining flights and handled on a superposition basis. When the damage is decoupled the mission mixed fatigue behavior can be related with a linear equation of the form $y = mx + b$ where y represents the life at air-to-air conditions and x represents the life for the air-to-ground and nontactical spectrum. Thus, failure will occur when the superposition of flight hours of the two types exceeds the failure condition. At the $K_tS_{max} = 97.0$ ksi level for instance, failure will occur when the damage term in the following equation exceeds unity

$$\text{DAMAGE} = \frac{(\text{HOURS EXPENDED}_{A-A})}{3500} + \frac{(\text{HOURS EXPENDED}_{ATG \,\&\, N-T})}{18000}$$

The mission mix study indicates that mission mix exerts a considerable influence on the fatigue behavior of the F-4E(S) spectrum investigated. Variations in the air-to-air content in the spectrum show almost a six to one variation in fatigue life whereas the other variations in fatigue spectra could change the life by less than 50% typically. Thus, mission mix appears to be the most significant variable for the spectrum utilized in this study.

CONCLUSIONS

1. The experimental results and analytical predictions made in this report indicate that the truncation methodology used by the contractor gives fatigue life and crack propagation behavior that is equivalent to that of the full spectrum.

2. The analytical predictions of the basic techniques of fatigue spectrum variation (such as reversing the spectrum, truncating the maximum loads and rank ordering the maximum loads of the spectrum) indicate that only minor variations in fatigue life behavior can be expected.

3. The analytical predictions for variations in the number of air-to-air mission flights in the 1000-hour spectrum indicate that the air-to-air mission is the major source of fatigue damage.

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TABLE I

LISTING OF HOURS TO FRACTURE FOR ALL SPECIMENS IN TEST PROGRAM

Specimen	Spectrum	Condition	Gross K_T	Max Gross Stress (ksi)	Flight Hrs to Fracture
1	Truncated	1/4 in. Dia. Open Hole	3.2	30.5	8700
2	Truncated	1/4 in. Dia. Open Hole	3.2	30.5	9300
3	Truncated	1/4 in. Dia. Open Hole	3.2	36.0	3300
4	Truncated	1/4 in. Dia. Open Hole	3.2	24	22900
5	Truncated	Notch	6.0	30.5	500
6	Truncated	Notch	6.0	30.5	400
7	Truncated	Notch	6.0	21.0	4100
8	Truncated	Notch	6.0	18.0	8600
9	Truncated	Precracked * Hole	∞	30.5	3300
10	Truncated	Precracked * Hole	∞	36.0	1600
11	Full	1/4 in. Dia. Open Hole	3.2	30.5	12900
12	Full	Notch	6	21.0	3000
13	Full	Precracked * Hole	∞	30.5	4200
14	Full	Precracked * Hole	∞	36.0	2100

* Corner cracks having surface lengths of 0.009, .015, 0.002, and 0.005 inch for specimens 9, 10, 13, and 14, respectively.

TABLE II

COMPARISON OF PREDICTED FATIGUE LIFE FOR

FULL AND LOW LOADS TRUNCATED SPECTRUM

Applied Stress Level, $K_t S_{max}$	Predicted Fatigue Life, Hours Full Spectrum 54,765 cycles/1000 Hr	Truncated Spectrum 19,080 cycles/1000 Hr
64.6	86,500	85,000
75.3	24,700	26,000
86.0	12,900	13,600
97.	8,500	8,800
107.5	6,000	6,300
118.4	5,900	5,600
129.0	5,000	6,000
140.	4,200	5,100
151.	3,100	3,800

TABLE III

CRACK GROWTH RATES AT SPECIFIC CRACK LENGTHS

Crack Length In.	Crack Growth Rate Per 1000 Hrs. - For 30.5 Gross Stress In./1000 Hrs.	For 36. Gross Stress In./1000 Hrs.
0.05	0.061	0.087
0.10	0.084	0.15
0.15	0.13	0.20
0.20	0.21	0.31
0.25	0.35	0.63

Rates associated with increased stress level are approximately a factor of 1.5 Faster than those at the lower level.

TABLE IV

EFFECT OF REVERSING ORDER OF ALL LOAD LEVELS

IN THE FULL F-4E/S SPECTRUM

Applied Stress Level, $K_t S_{max}$	Predicted Fatigue Life, Hours	
	Basic Spectrum	Reversed Spectrum
96.9	8,500	8,500
116.2	5,200	5,100
127.0	5,000	5,100
185.1	750	750

TABLE V

EFFECT OF HI-LO AND LO-HI PEAK LOAD RAMPING ON THE FATIGUE BEHAVIOR WITH THE FULL F-4E/S SPECTRUM

Applied Stress Level, $K_t S_{max}$	Predicted Fatigue Life, Hours: Hi-Lo Threshold 85.7%	78.5%	Lo-Hi Threshold 85.7%	78.5%	Full Spectrum
64.6	73,600	69,000	61,000	75,000	86,500
75.3	20,000	19,000	18,000	20,000	24,700
86.0	10,700	9,400	10,200	10,000	12,900
97.	-	6,300	7,000	6,900	8,500
107.5	5,400	4,600	5,100	5,000	6,000
118.4	-	4,100	4,600	4,300	5,900
129.0	-	3,900	4,600	4,000	5,000
140.0	4,100	3,500	3,800	3,600	4,200
151.0	2,800	2,800	2,800	2,900	3,100

TABLE VI

COMPARISONS OF FATIGUE LIFE PREDICTIONS FOR

PEAK LOAD TRUNCATION FOR THE FULL SPECTRUM

Applied Stress Level, $K_t S_{max}$	Predicted Fatigue Life, Hours		
	Maximum Truncated at 85.7%	Maximum Truncated at 92.8%	Full Spectrum
64.6	140,000	95,000	87,000
75.3	30,000	23,000	25,000
86.1	11,000	12,000	13,000
96.8	7,700	8,200	8,500
107.6	5,600	5,800	6,000
118.4	4,200	4,700	5,900
129.2	4,000	4,700	5,000
139.9	3,900	4,200	4,200
150.7	3,300	3,300	3,100

TABLE VII

EFFECT OF MISSION MIX ON THE LOW LOADS TRUNCATED SPECTRUM

Applied Stress Level, $K_t S_{max}$	Predicted Fatigue Life, Hours		
	Low Loads Truncated Spectrum	Truncated Spectrum W/O A-A	Truncated Spectrum W/O ATG & Non-T
	19,080 cycles/1000 Hrs	17,964 cycles/1000 Hrs	22,428 cycles/1000 Hrs
64.6	85,000	167,000	34,000
75.3	26,000	52,000	9,300
86.0	13,600	31,000	5,600
97.0	8,800	18,000	3,500
107.5	6,300	12,700	2,500
118.4	5,600	10,500	2,200
129.0	6,000	9,400	2,700
140.0	5,100	7,100	2,600
151.0	3,800	4,800	2,200

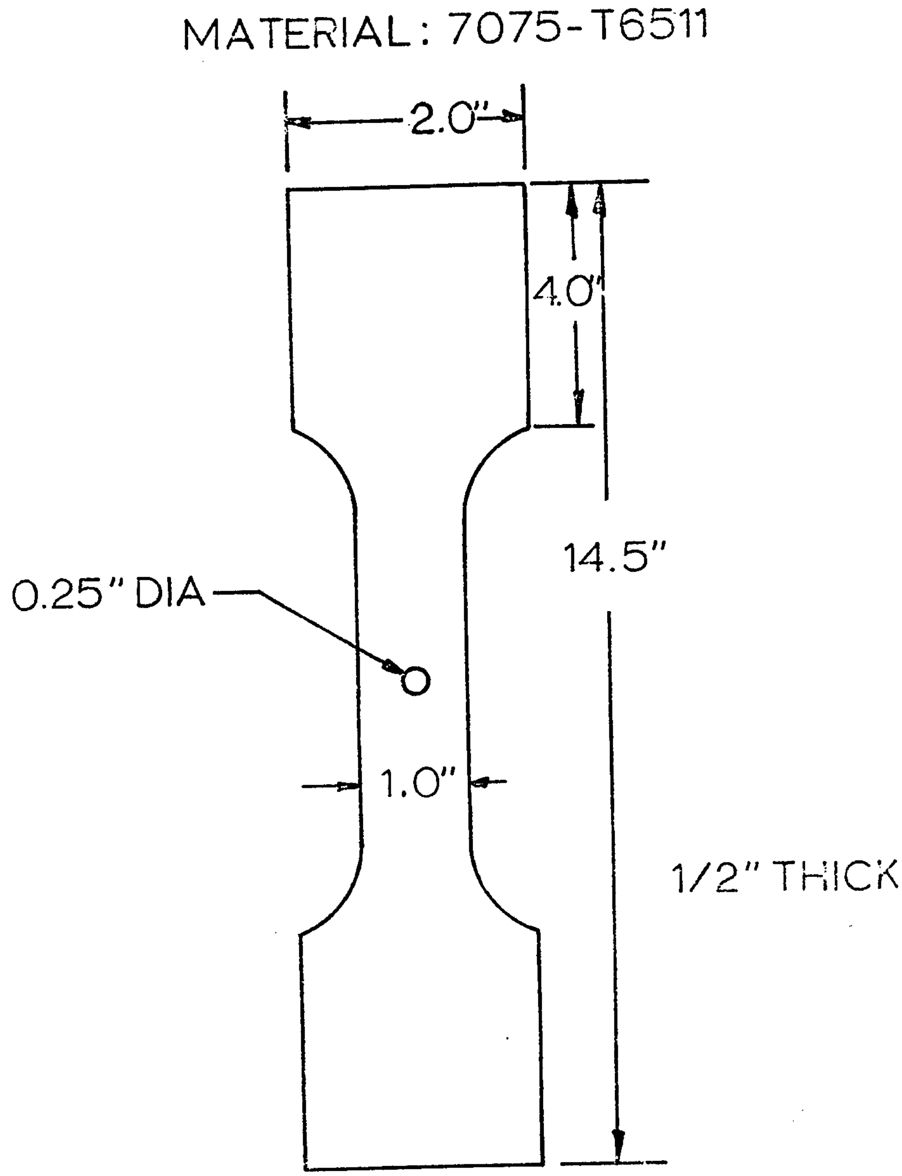

FIG. 1. SPECIMEN GEOMETRY FOR $K_T = 3.2$ COUPON

MATERIAL: 7075-T6511

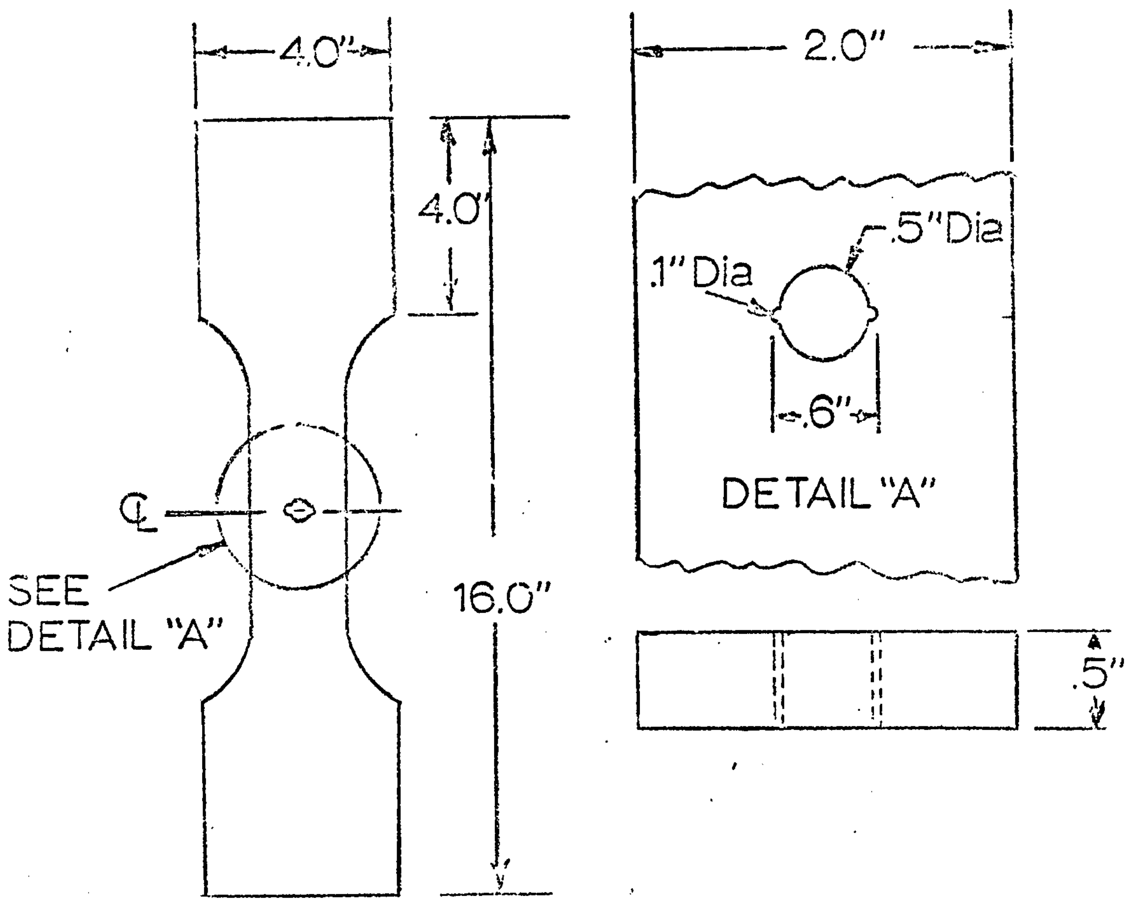

FIG. 2. SPECIMEN GEOMETRY FOR K_T = 6.0 COUPON

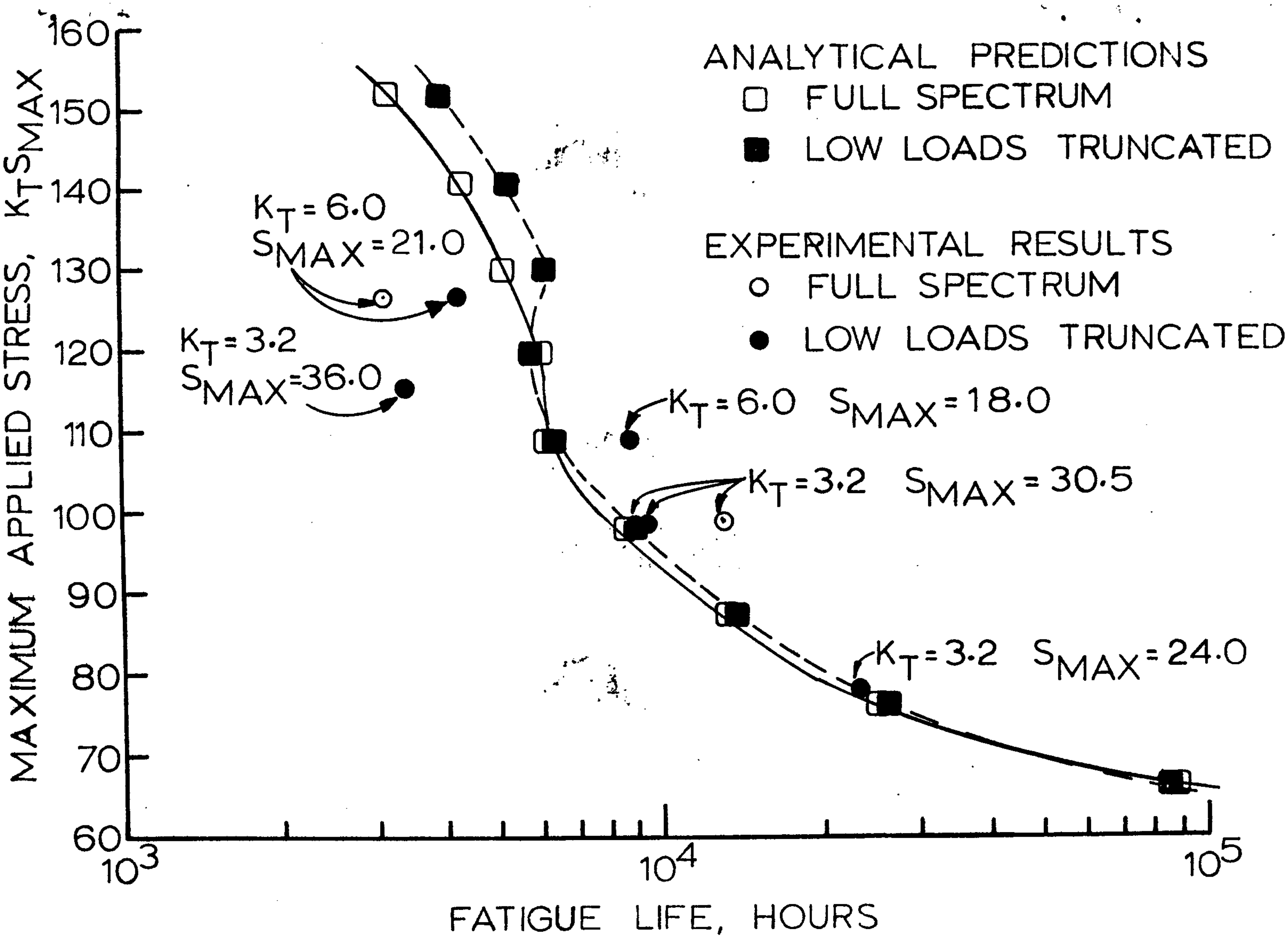

FIG. 3. EFFECT OF LOW LOAD TRUNCATION ON FATIGUE BEHAVIOR WITH FLIGHT-BY-FLIGHT SPECTRUM

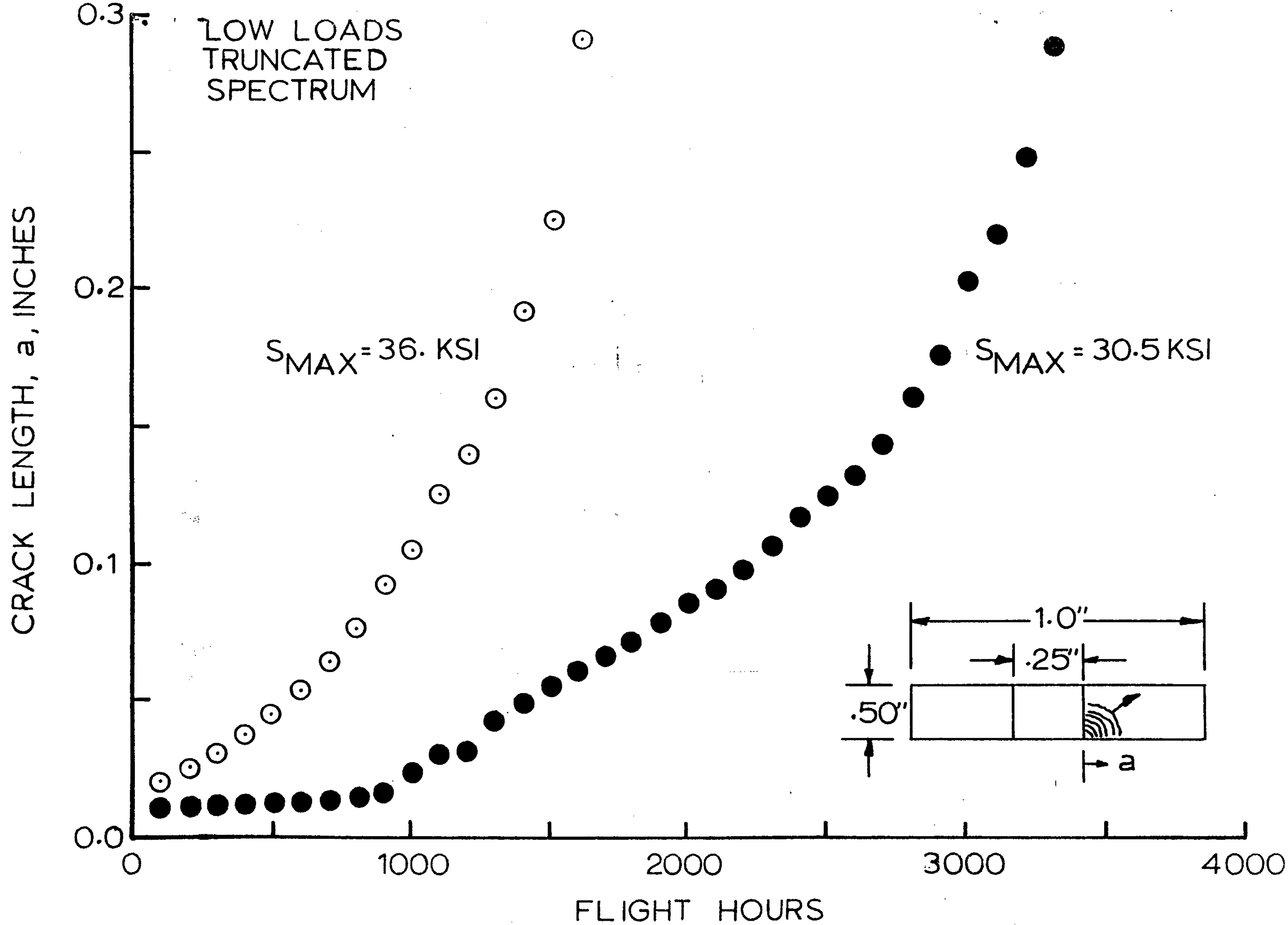

FIG. 4. EXPERIMENTAL PROPAGATION BEHAVIOR OF CORNER CRACK WITH LOW LOAD TRUNCATED F-4E/S SPECTRUM

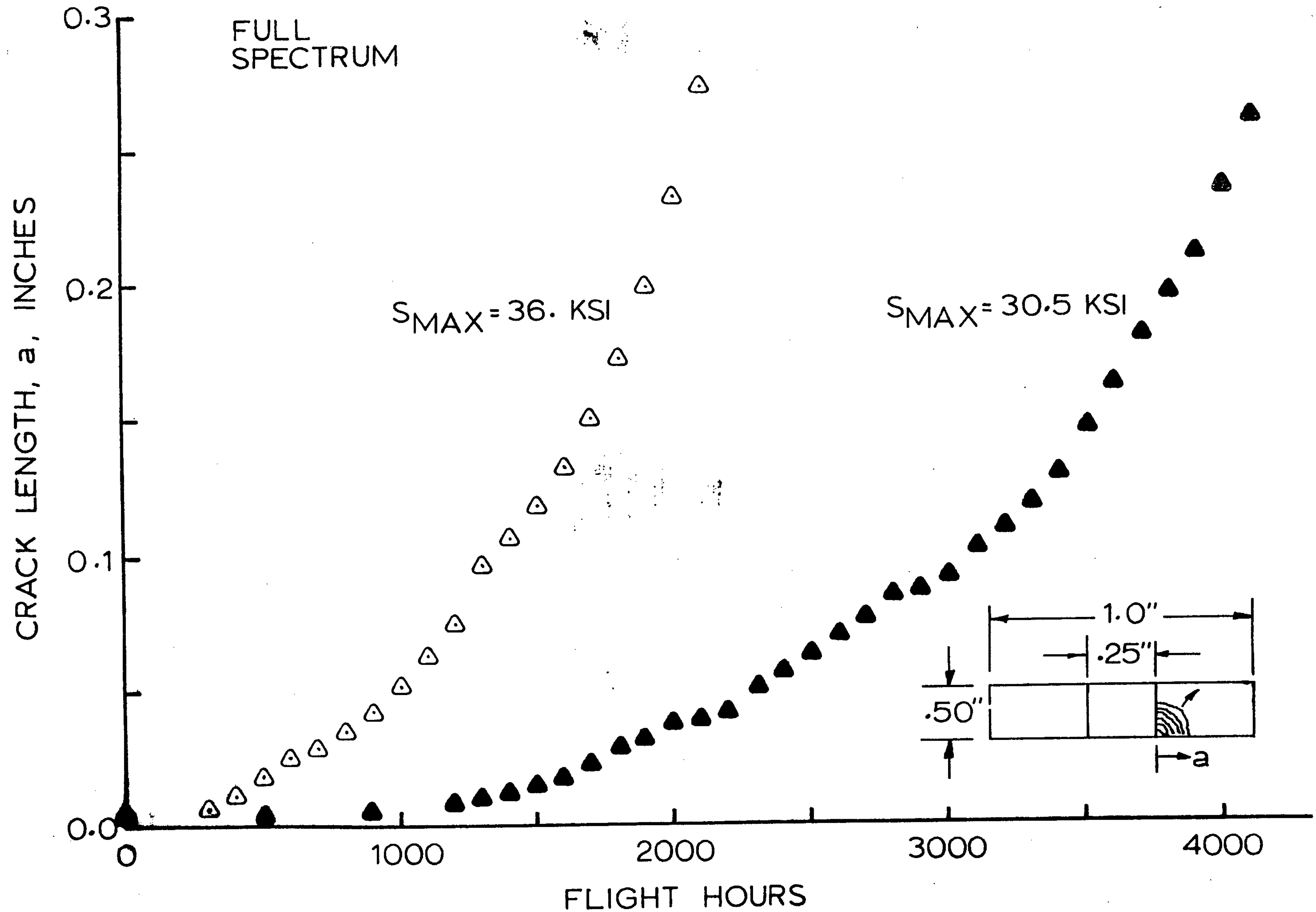

FIG. 5. EXPERIMENTAL PROPAGATION BEHAVIOR OF CORNER CRACK WITH

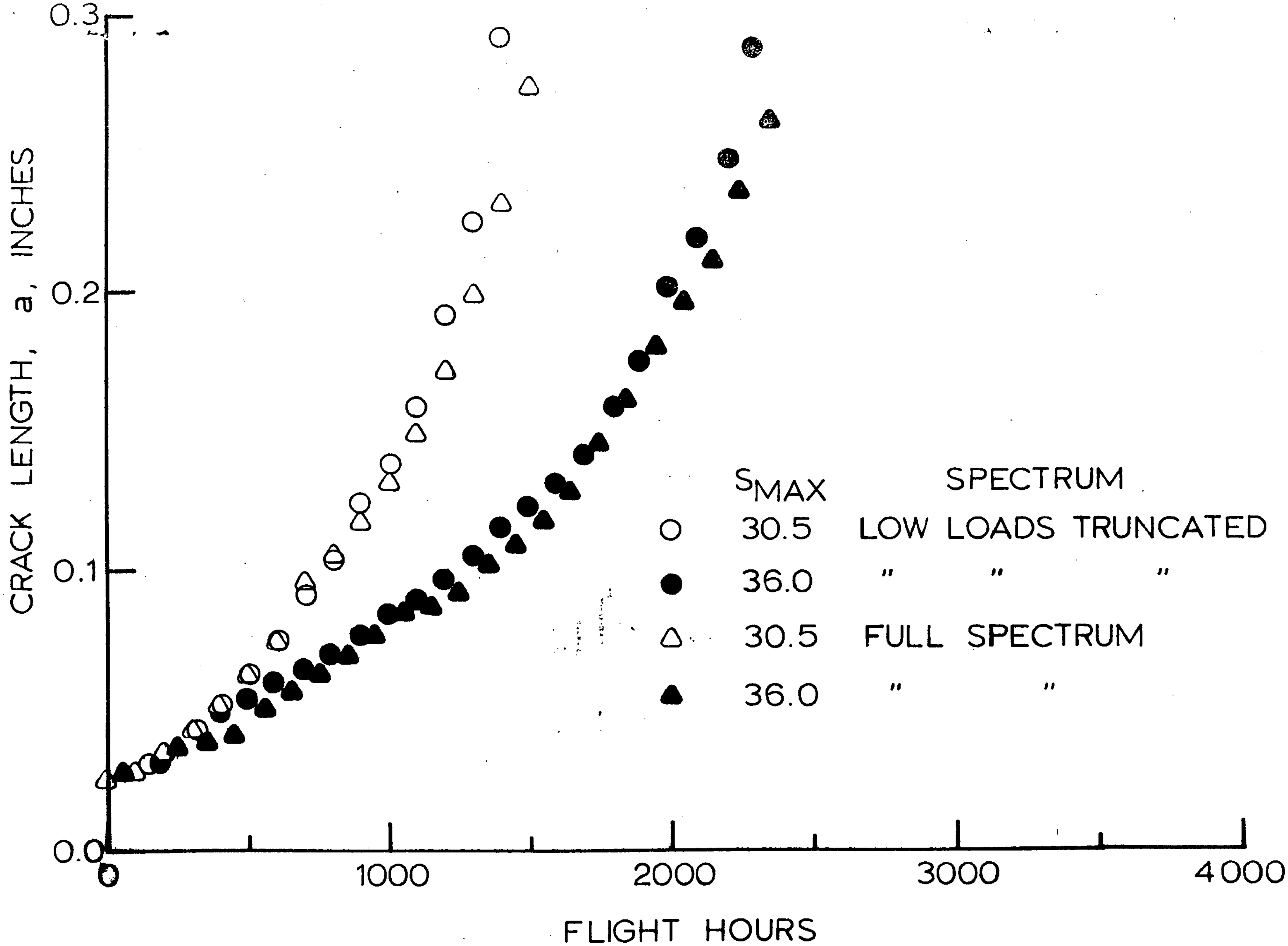

FIG. 6. EXPERIMENTAL PROPAGATION BEHAVIOR OF CORNER CRACK FOR BOTH SPECTRA NORMALIZED TO AN INITIAL CRACK LENGTH OF 0.025 INCHES

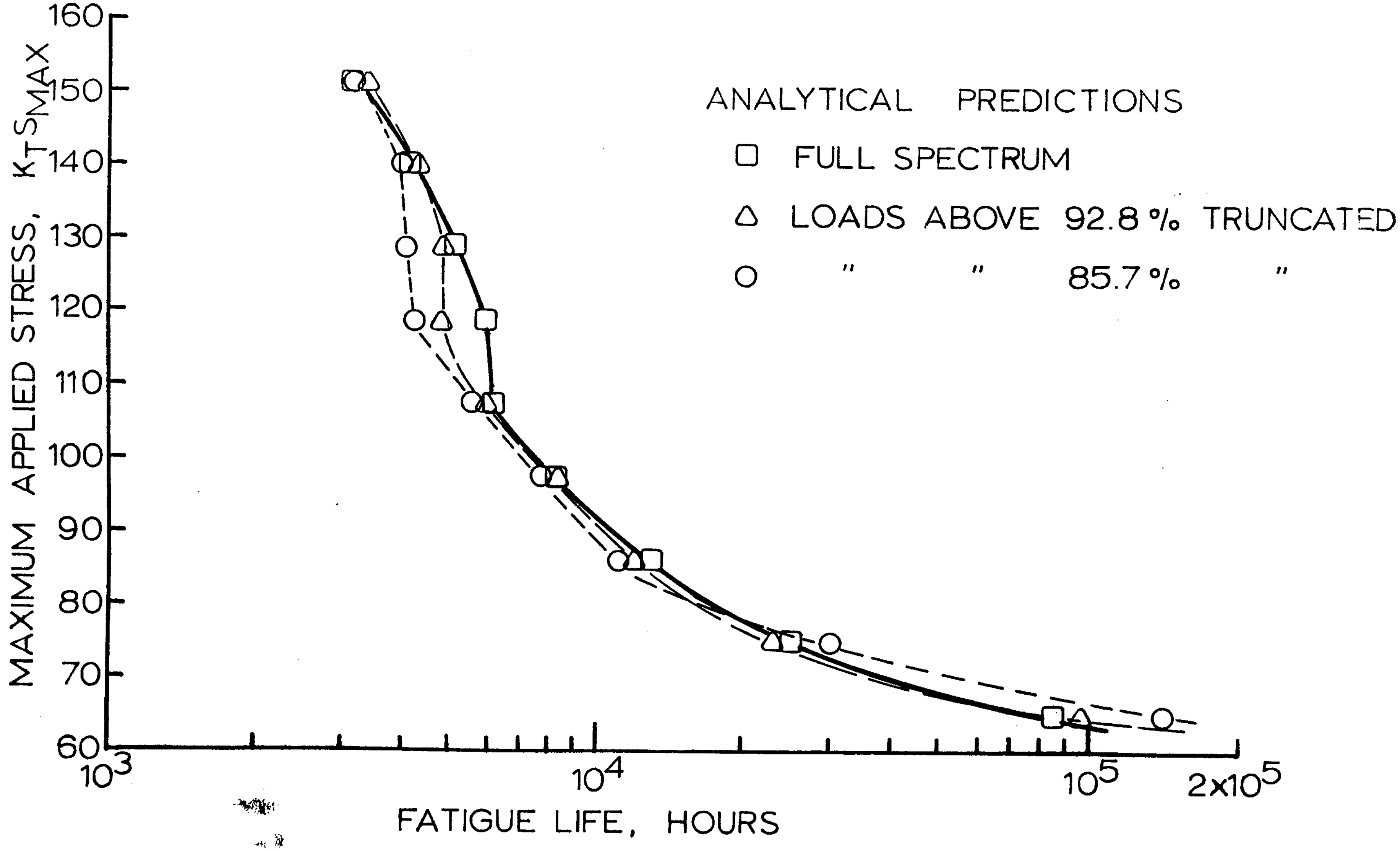

FIG. 7. EFFECT OF PEAK LOAD TRUNCATION ON PREDICTED FATIGUE BEHAVIOR OF FULL F-4E/S SPECTRUM

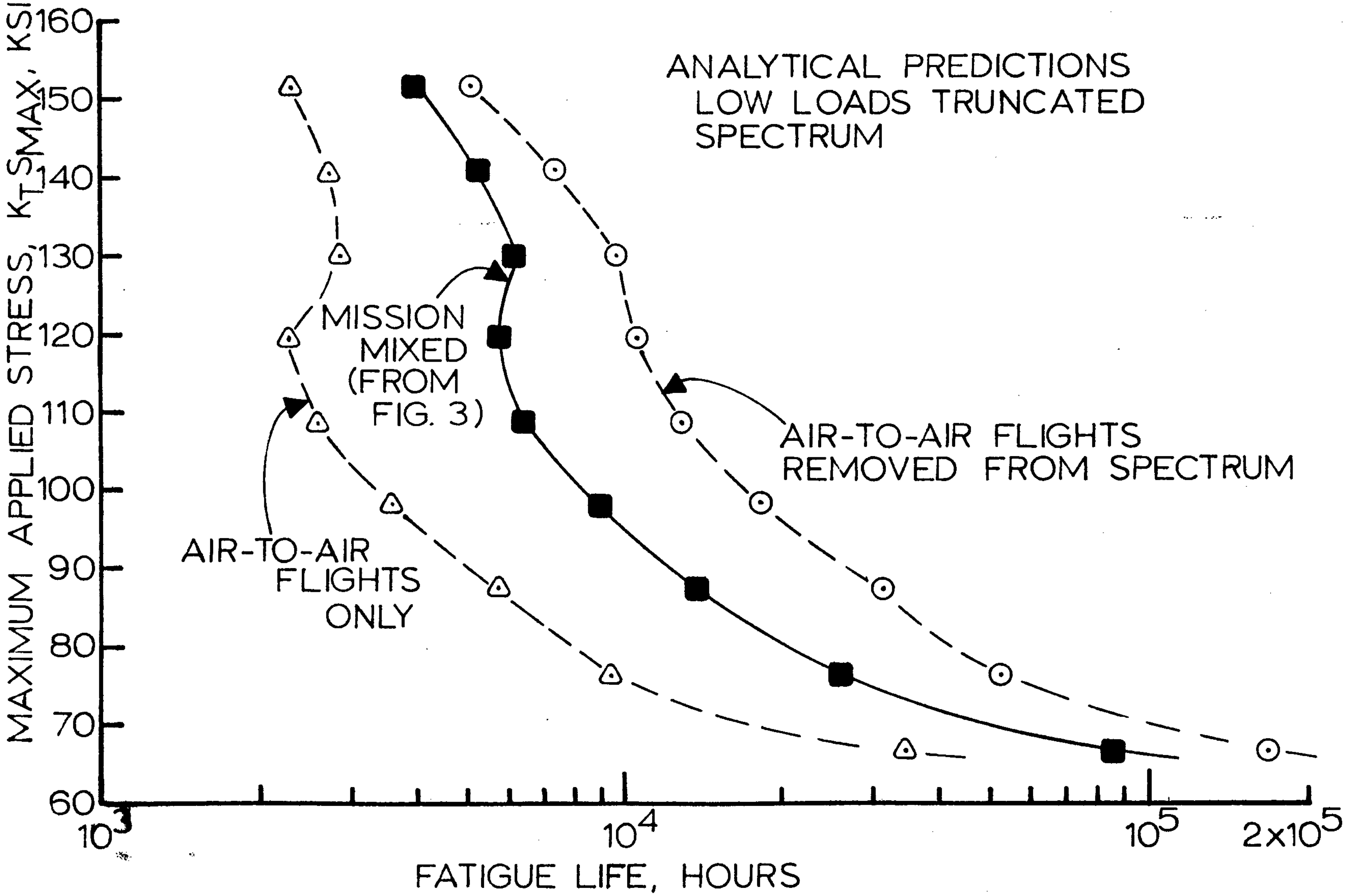

FIG. 8. EFFECT OF MISSION MIX ON THE PREDICTED FATIGUE BEHAVIOR OF LOW LOAD TRUNCATED F-4E/S SPECTRUM

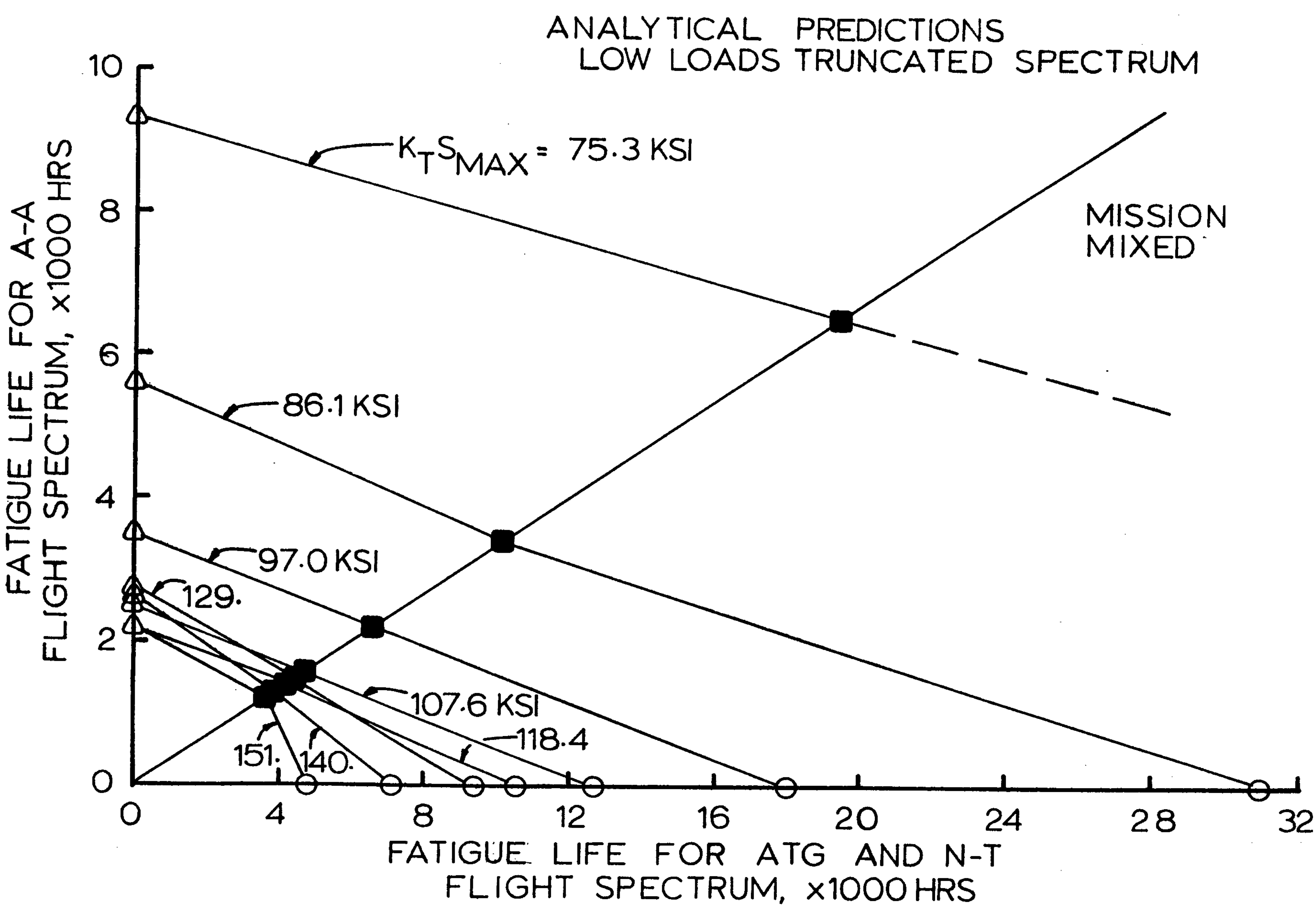

FIG. 9. INTERACTION GRAPH COMPARING THE EFFECT OF MISSION MIX ON THE PREDICTED FATIGUE BEHAVIOR OF LOW LOAD TRUNCATED F-4E/S SPECTRUM